

## $\gamma\gamma \rightarrow \gamma\gamma$ scattering in ultrarelativistic UPC

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We discuss diphoton semi(exclusive) production in ultraperipheral lead-lead collisions at energy of  $\sqrt{s_{NN}} = 5.5$  TeV (LHC) and in proton-proton collisions at  $\sqrt{s_{pp}} = 7$  TeV (LHC) and  $\sqrt{s_{pp}} = 100$  TeV (FCC). The nuclear calculations are based on equivalent photon approximation in the impact parameter space. The cross sections for elementary  $\gamma\gamma \rightarrow \gamma\gamma$  subprocess are calculated including three different mechanisms: box diagrams with leptons and quarks in the loops, a VDM-Regge contribution with virtual intermediate hadronic excitations of the photons and the two-gluon exchange contribution. We get relatively high cross sections in heavy ion collisions. This opens a possibility to study the light-by-light (quasi)elastic scattering at the LHC. We find that the cross section for elastic  $\gamma\gamma$  scattering could be measured in the lead-lead collisions for the diphoton invariant mass up to  $W_{\gamma\gamma} \approx 15 - 20$  GeV. Our Standard Model predictions are compared to a recent ATLAS experimental result. We present differential distributions for  $\text{PbPb} \rightarrow \text{PbPb}\gamma\gamma$  and  $\text{pp} \rightarrow \text{pp}\gamma\gamma$  reaction.

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\* A footnote may follow.

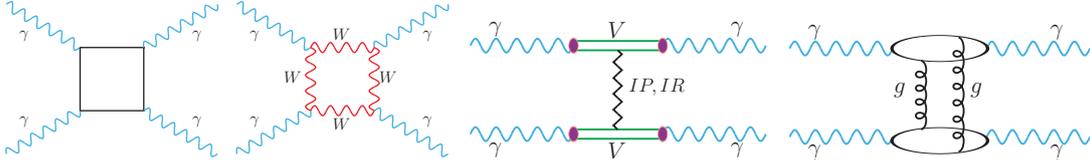
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## 1. Introduction

In classical Maxwell theory photons/waves/wave packets do not interact. In contrast, in quantum theory they can interact via quantum fluctuations. So far only inelastic processes, i.e. production of hadrons or jets via photon-photon fusion could be measured. It was realized only recently that ultraperipheral collisions (UPC) of heavy-ions can be also a good place where photon-photon elastic scattering could be tested experimentally. Our theoretical predictions [1] became a motivation for experimental groups to perform corresponding experimental studies. Recently the ATLAS Collaboration observed 13 events for light-by-light scattering in Pb-Pb UPC [2]. We shall discuss our results and future possibilities.

## 2. $\gamma\gamma \rightarrow \gamma\gamma$ elementary cross section



**Figure 1:** Light-by-light scattering mechanisms with the lepton and quark loops (first panel) and for the intermediate  $W$ -boson loop (second panel). The third panel represents VDM-Regge mechanism and the last panel is for two-gluon exchange.

The lowest order QED mechanisms with elementary particles are shown in two first diagrams of Fig. 1. The first diagram is for lepton and quark loops and it dominates at lower photon-photon energies ( $W_{\gamma\gamma} < 2m_W$ ) while the next diagram is for the  $W$  (spin-1) boson loops and it becomes dominant at higher photon-photon energies ([3, 4]). The one-loop box amplitudes were calculated by using the Mathematica package `FormCalc` and the `LoopTools` library. We obtained good agreement when confronting our result with those in [3, 5, 6]. In Ref. [6] the authors considered the QCD and QED corrections to the one-loop fermionic contributions in the limit ( $\hat{s}, |\hat{t}|, |\hat{u}| \gg m_f^2$ ). The corrections are quite small numerically so the LO computations are satisfactory. In the last two diagrams of Fig. 1 we show processes that are the same order in  $\alpha_{em}$  but higher order in  $\alpha_s$ . They were discussed only by our group. The third diagram presents situation where both photons fluctuate into virtual vector mesons ( $\rho, \omega, \phi$ ). The last diagram shows two-gluon exchange mechanism which is formally three-loop type. Its contribution to the elastic scattering of photons at high energies was considered first in the pioneering work [7]. Indeed in the limit where the Mandelstam variables of the  $\gamma\gamma \rightarrow \gamma\gamma$  process satisfy  $\hat{s} \gg -\hat{t}, -\hat{u}$ , major simplifications occur and this process becomes tractable. In our treatment, we include finite fermion masses, the full momentum structure in the loops as well as all helicity amplitudes [8].

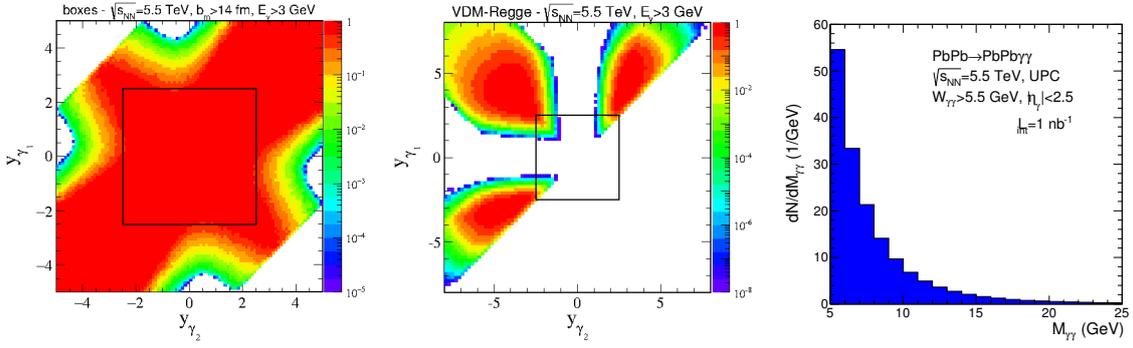
## 3. Light-by-light scattering in UPC

A nuclear cross section is calculated in equivalent photon approximation (EPA) in the impact parameter space. The total (phase space integrated) cross section is expressed through the five-fold

integral (for more details see e.g. [9])

$$\sigma_{A_1 A_2 \rightarrow A_1 A_2 \gamma\gamma}(\sqrt{s_{A_1 A_2}}) = \int \sigma_{\gamma\gamma \rightarrow \gamma\gamma}(W_{\gamma\gamma}) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) d^2 b d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\gamma\gamma}, \quad (3.1)$$

where  $W_{\gamma\gamma}$  and  $Y_{\gamma\gamma}$  is invariant mass and rapidity of the outgoing  $\gamma\gamma$  system. Energy of photons is expressed through  $\omega_{1/2} = W_{\gamma\gamma}/2 \exp(\pm Y_{\gamma\gamma})$ .  $\mathbf{b}_1$  and  $\mathbf{b}_2$  are impact parameters of the photon-photon collision point with respect to parent nuclei 1 and 2, respectively, and  $\mathbf{b} = \mathbf{b}_1 - \mathbf{b}_2$  is the standard impact parameter for the  $A_1 A_2$  collision. In practical calculation we use  $S_{abs}^2 = \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A)$ . The photon flux ( $N(\omega, b)$ ) is expressed through a nuclear charge form factor of the nucleus. In our calculations we use a realistic form factor which is a Fourier transform of the charge distribution in the nucleus. More details can be found e.g. in [1, 9].



**Figure 2:** Contour representation (first two panels) of two-dimensional ( $d^2\sigma/dy_{\gamma_1} dy_{\gamma_2}$  in nb) distribution in rapidities of the two photons in the laboratory frame for box (left panel) and VDM-Regge (middle panel) contributions. Nuclear calculations were done for  $\sqrt{s_{NN}} = 5.5$  TeV. The last panel shows distribution of expected number of counts in 1 GeV bins for cuts on  $W_{\gamma\gamma} > 5.5$  GeV and  $\eta_\gamma < 2.5$ .

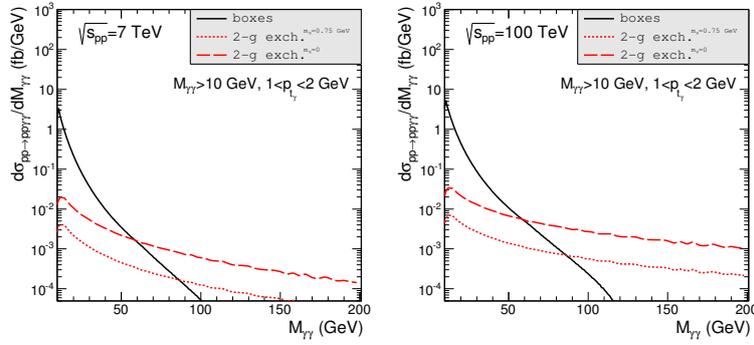
In our recent papers we tried to answer the question whether the reaction can be measured with the help of LHC detectors. Then we have to generalize Eq. (3.1) by adding extra integration over additional parameter related to angular distribution for the subprocess [1]. The two first panels of Fig. 2 show two-dimensional distributions in photon rapidities. The calculation was done at the LHC energy  $\sqrt{s_{NN}} = 5.5$  TeV. Here we imposed cuts on energies of photons in the laboratory frame ( $E_\gamma > 3$  GeV). We obtain very different distributions for box and VDM-Regge mechanisms. In both cases the influence of the imposed cuts is significant. In the case of the VDM-Regge contribution we observe non continuous behaviour which is caused by the strong transverse momentum dependence of the elementary cross section (see Fig. 4 in Ref. [1]) which causes that some regions in the two-dimensional space are almost not populated. The second half of the  $(y_{\gamma_1}, y_{\gamma_2})$  space can be obtained from the symmetry around the  $y_{\gamma_1} = y_{\gamma_2}$  diagonal. Clearly the VDM-Regge contribution does not fit to the main detector ( $-2.5 < y_{\gamma_1}, y_{\gamma_2} < 2.5$ ) and extends towards large rapidities. In this case we show much broader range of rapidity than for the box component. We discover that maxima of the cross section associated with the VDM-Regge mechanism are at  $|y_{\gamma_1}|, |y_{\gamma_2}| \approx 5$ . Unfortunately this is below the limitations of the ZDCs for ATLAS ( $|\eta| > 8.3$ ) and CMS ( $|\eta| > 8.5$ ). The last panel of Fig. 2 presents the numbers of counts in the 1 GeV intervals expected for assumed integrated luminosity:  $L_{int} = 1$  nb $^{-1}$  typical for UPC at the LHC. In this calculation we

imposed cuts on photon-photon energy and (pseudo)rapidities of both photons. With the assumed luminosity one can measure invariant mass distribution up to  $M_{\gamma\gamma} \approx 15$  GeV.

We studied the mechanism of elastic photon-photon scattering also in  $pp \rightarrow pp\gamma\gamma$  reaction. In our calculations we neglect the gap survival factor. The cross section of  $\gamma\gamma$  production in proton-proton collisions takes the simple parton model form

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1 \gamma^{(el)}(x_1) x_2 \gamma^{(el)}(x_2) \overline{|M_{\gamma\gamma \rightarrow \gamma\gamma}|^2}. \quad (3.2)$$

Here  $y_{1/2}$  is the rapidity of final state photon,  $p_t$  is the photon transverse momentum and  $x_{1/2} = p_t/\sqrt{s} (\exp(\pm y_1) + \exp(\pm y_2))$ . The calculation for proton-proton collisions are done as usually in the parton model with elastic photon distributions expressed in terms of proton electromagnetic form factors. Detailed description of the cross section for  $pp \rightarrow pp\gamma\gamma$  reaction can be found in our paper [8].



**Figure 3:** Distribution in invariant mass of the produced photons for  $\sqrt{s_{pp}} = 7$  TeV (LHC) and  $\sqrt{s_{pp}} = 100$  TeV (FCC) for cuts on photon transverse momenta specified in the figure legend. No cuts on photon rapidities are applied here.

The nuclear distribution in the diphoton invariant mass is shown in Fig. 3. The two-gluon distribution starts to dominate over the box contribution only above  $M_{\gamma\gamma} > 50$  GeV for  $1 \text{ GeV} < p_t < 2 \text{ GeV}$ . However, the cross section in this region is rather small. The situation for the LHC (left panel) and for Future Circular Collider (FCC) energy (right panel) is rather similar. The dominance of the two-gluon exchange over the box contribution takes place more or less at the same diphoton invariant masses.

#### 4. Conclusion

In our recent papers we studied how to measure elastic photon-photon scattering in ultrarelativistic lead-lead UPC as well as proton-proton collisions. The cross section for photon-photon scattering was calculated taking into account well known box diagrams with elementary standard model particles (leptons and quarks), a VDM-Regge component as well as a two-gluon exchange, including massive quarks, all helicity configurations of photons and massive and massless gluon. For the  $PbPb \rightarrow PbPb\gamma\gamma$  reaction we identified regions of the phase space where the two-gluon contribution should be enhanced relatively to the box contribution. The region of large rapidity

difference between the two emitted photons and intermediate transverse momenta  $1 \text{ GeV} < p_t < 2\text{-}5 \text{ GeV}$  seems optimal in this respect.

This year the ATLAS Collaboration published a new result [2] for light-by-light scattering in quasi-real photon interactions which come from ultraperipheral lead-lead collisions at  $\sqrt{s_{NN}}=5.02 \text{ TeV}$ . The measured fiducial cross section which includes limitation on photon transverse momentum, photon pseudorapidity, diphoton invariant mass, diphoton transverse momentum and diphoton acoplanarity, were measured to be  $70 \pm 20 \text{ (stat.)} \pm 17 \text{ (syst.) nb}$ . This result is compatible with the value of  $49 \pm 10 \text{ nb}$  predicted by us for the ATLAS cuts and experimental luminosity.

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